THE RELATION OF RADIOACTIVITY TO VULCANISM

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Within the last year or two those working in the rapidly growing science of radioactivity and sub-atomic systems have discovered a number of properties and relations that bear strongly on earth processes and theories, and that are of daily increasing interest to the geologist, many of whose problems are being made to assume a new light. Very recently (April, 1906) Major Dutton[1] presented a paper to the National Academy of Sciences in which the results of the investigators of radioactivity have been brought into relation with geological phenomena to construct a definite explanation of volcanic action.

In discussing the competency of radioactivity to produce the local high-temperature effects which are essential to volcanic action, it is desirable to consider first the relationship of radioactivity to the general thermal condition of the earth's interior. Since Major Dutton's paper was prepared, R. J. Strutt[2] has published an account of some tests made on various igneous rocks from different parts of the world, with the result that the earlier conclusions as to the relation of earth heat to radioactivity are made much more secure and definite. In general it may be said that all the igneous rocks examined (they were selected to represent different parts of the earth and different rock types) show distinct radioactivity, the most active being the more acid granites and syenites; the least active, basalts and various ultrabasic rocks. Division into more active and less active specimens does not correspond absolutely to rock types, but very generally so. The range in content is calculated at from 1.84×10^{-12} to 25.5×10^{-12} grams of radium per cubic centimeter of rock, or

[1] See *Popular Science Monthly*, June 1906, pp. 542–50; also *Journal of Geology*, Vol. XIV, pp. 259–68 (June, 1906).

[2] R. J. Strutt, "On the Distribution of Radium in the Earth's Crust, and on the Earth's Internal Heat," *Proceedings of the Royal Society*, Ser. A, Vol. LXXVII (1906), pp. 472–85.

0.613×10^{-12} to 9.56×10^{-12} grams of radium per gram of rock. All samples showing above 3.37×10^{-12} grams of radium per gram of rock are granites or syenites; the basalts and peridotites are all below 1.86×10^{-12}.

Strutt shows that if the interior of the earth be considered at thermal equilibrium, and if the whole amount of heat is due only to radium (part must be due to uranium and other active elements), and "always supposing that the heat production of radium is not materially diminished, under conditions prevailing inside the earth;" if, further, the radium be considered evenly distributed throughout the earth mass, it cannot much exceed 1.75×10^{-13} grams per cubic centimeter. Rutherford,[1] using somewhat different values for temperature gradient, etc., calculates the equivalent in radium bromide as 2.6×10^{-13} grams per cubic centimeter or 1.52×10^{-13} grams radium. But the weakest rock examined (Disco Island basalt) gives tests over ten times this amount, and the granites 240 or 250 times! The question becomes, then, why is the interior so cool? Strutt offers the explanation that only the external or crustal portions of the earth are radioactive. Taking the moderate value of 5×10^{-12} grams radium per cubic centimeter as representing the average rocks of the crust, radioactive rocks need extend only 45 miles below the surface to establish the present temperature gradient. If we assume that the granites represent the constitution of the outer crust, 5 or 6 miles are sufficient; if basalts of the weakest activity so far examined, only 96 miles are necessary.[2]

As supporting his assumption of a crustal layer of 45 miles or less in thickness and of different constitution from the interior, Strutt refers to the conclusions of Professor Milne that a study of the propagation of earthquake waves through the earth's interior indicates a rather abrupt change at about 30 miles' depth, the material below that being rather uniform throughout the globe.

[1] Rutherford, *Radioactivity*, 2d ed. (Cambridge, 1905), p. 494.

[2] To account for the greater density of the interior of the earth, and from the hint given by the constitution of meteorites, we may suspect that the inner parts of the earth are of "basic" materials. The limit of basic materials tested is found in meteoric iron, which gives no measurable radioactivity. We may well suspect, then, that the radioactive crust is rather thin, the amount of activity not being constant to a certain definite point, but gradually decreasing toward a zero value at somewhere between 30 and 90 miles in depth.

There are other highly suggestive features to Strutt's paper, but let us consider the geological bearing of those already presented. First, it seems probable that we have a hitherto unconsidered supply of heat capable of maintaining for an exceedingly long period the known temperature gradient within the earth, and, in fact, necessitating the introduction of restrictions as to interior distribution in order to account for the lack of a higher than the observed gradient. As Strutt suggests, an assumption that the earth is getting hotter is "not likely to be regarded with favor." But that we have a condition of equilibrium seems quite possible, and, if not equilibrium, there must at least be a condition of very much slower cooling than the calculated loss by conduction to the surface would indicate. In this latter case we may still assume that the earth's heat has been derived from two groups of sources: one, the initial condition and relative positions of its constituent atoms, molecules, and masses, acting as outlined by one of the nebular or solid accretion hypotheses; the other, radioactivity or, more broadly, sub-atomic changes. This latter has probably varied but little for a long period of time.[1] If the condition at present is one of practical equilibrium, or not far removed therefrom, it means that the effects of any original high temperature (such as assumed by the nebular hypotheses) are now exceedingly slight, and as, if such original temperature ever existed, it must have died out with a gradually decreasing rate, its effects must have been slight for a long period of time. It would seem, therefore, that the utmost caution should be used in any attempt to explain characteristics of the geological record, especially in its later part, in terms of any cosmic hypothesis assuming initial high temperatures.

The folding of zones of the earth's crust into mountain ranges or mountain systems and certain other diastrophic changes, in particular those giving rise to earthquakes, are very commonly referred, in whole or in part, to the contraction of the earth as it cools. But the indica-

[1] It is supposed on very suggestive evidence that uranium is the parent of radium. Geologically considered, radium has a comparatively short life, breaking down with a velocity that decreases according to an exponential law and reaching half value in 1,300 years. The supply of radium is apparently maintained by the transformation of uranium, which is an exceedingly slow process, varying in velocity similarly to radium and reaching half value, according to Rutherford's calculation (*loc. cit.*, p. 458), in about 600,000,000 years or more.

tions from Strutt's measurements are to the effect that the earth is either not appreciably cooling or is doing so with excessive slowness. Post-Tertiary foldings can hardly be referred to such a cause, and probably early Tertiary and even Mesozoic movements should be excluded. On account of the fundamental similarity of the geological history of the steps leading to the formation of the systems of folds produced at different periods, it would seem reasonable to assume very similar causes and to believe that, at least since the opening of the Paleozoic,[1] contraction due to cooling is as unnecessary to explain the earlier as the later foldings.

If radioactivity may be accepted as a sufficient cause for the present thermal gradient, we must also conclude that no major contractional movements under the influence of self-gravitation have taken place in recent geological time of such magnitude as to give rise to any great addition of heat of mechanical origin.

Leaving now the general aspect and turning to the particular subject of volcanoes, we may accept radioactivity as the cause of the major part or all of the general internal heat, at least in late geologic time, and still have all of the special problems of vulcanism to face that have confronted those who assume other origins for the temperature gradient, and the same explanations might do equally well irrespective of the type of general hypothesis.

But Major Dutton[2] has put forward a more particular hypothesis to the effect that volcanoes are caused by local excessive radioactivity which melts small areas of rock near the surface and allows the expansive force of "water vapor to lift its covering and force a way to the surface." The rest of this communication is devoted to a discussion of the points involved in this very interesting and ingenious hypothesis.

The first point is the shallowness of the reservoir. Dutton estimates that "most of the volcanic eruptions originate at depths between one mile and two and one-half miles." The bearing of this point on the local-radiation hypothesis of volcanoes is that at such shallow depths the general earth heat cannot be invoked to produce the tem-

[1] The post-Archean (pre-Paleozoic) foldings are sufficiently different—especially in their incomparably wide distribution and almost universal association with abundant plutonic intrusive masses—to invite a special treatment.

[2] *Loc. cit.*

peratures involved, and we must therefore assume some special heating agent in the cooler portions of the earth's crust. For by the normal temperature gradient 1,000° C. would be reached at not much less than about twenty miles[1] below the surface.

It would seem that the general chemical characters of lavas would be fatal to this contention. If the material extruded from volcanoes was chiefly derived from the melting of rock at the depth of from one to two and one-half miles, or even considerably deeper, the reservoirs would be largely within the zone of sediments, and lavas should frequently have a composition derivable from the major sedimentary types alone or mixed in various ways. But igneous rocks have a rather definite range in chemical composition, and there are general and important differences between igneous types and at least the major sedimentary types. The chief reasons for these differences are easily explained by the nature of the processes leading up to sedimentation. The materials of the igneous rocks are worked over and sorted on lines of mechanical and chemical resistance, etc., and from them are leached much or all of the more soluble materials, a large part of which passes down and becomes a permanent constituent of the waters of the sea, a corresponding deficit appearing in the composition of the sediments.

Petrologists have recognized for some years that lavas in general cannot be considered as derived from molten sediments, and yet, if the reservoirs were limited to the first few miles of the crust, a large proportion of them should have such origin. The abundant evidence gathered along this line demands that lavas be derived entirely from below the zone of sedimentary rocks.

Volcanoes which arise from the deep sea cannot be considered as affected one way or the other by this line of argument, for we know nothing of the chemical nature of even the shallow layers of the suboceanic crust. Furthermore, there are continental volcanoes that do not occur in sediment-covered provinces. Of these probably the most common are found on granitoid bedrocks. Many of the Tertiary volcanoes of the Sierra Nevada were of this type, the lavas over considerable areas breaking through granitoid rocks, with only here and

[1] According to Strutt's curve, based on a uniformly radioactive crust 45 miles deep overlying a non-radioactive interior, 1,000° C. would be reached at about 18 miles, 1,200° at about 23 miles.

there patches of metamorphosed sediments. If the lavas coming up through such rocks were chiefly rhyolites or dacites, with perhaps complementary types derivable from these by differentiation, they might be considered to have been formed by melting of the granitic or granodioritic bedrock material; but we find a great profusion of andesites during the later Tertiary—hornblende andesites, pyroxene andesites, hypersthene and other basic andesites (and latites), and finally basalts rich in olivine. This phenomenon of basic rocks breaking through and pouring out over granites is not uncommon in other regions.

Can we reasonably imagine that in a great batholitic mass of granite, several or many hundred square miles in area, the granitic material is only a mile or two thick, and there changes into basic diorite or gabbro? Many granitic areas occur in the western United States through which basic lavas in abundance have broken, yet erosion, which has in many cases deeply dissected such masses shows nowhere such an internal structure.[1]

Further information as to depth of focus may be derived from sedimentary districts where, after the extrusion of lavas, the rocks have been uplifted, tilted, and eroded. The thickness of sediments necessarily traversed by a lava in rising to the surface at some definite stratigraphic horizon can frequently be calculated closely enough for our present purpose. In the Coast Ranges of California the late Tertiary lavas have often had to make their way through several miles of Mesozoic and Tertiary rocks to reach the surface. These volcanic rocks do not show the characteristics of melted sediments; nor have the exceedingly active earth processes at the end of the Tertiary, which have uplifted and folded and eroded the rocks in such a way as to expose frequently the whole Tertiary and Cretaceous series—not rarely 20,000 to 30,000 feet in thickness[2]—brought to light any of the reservoirs formed by the melting of rock *in situ*. They frequently testify to the fact that the sources were still lower, by the dikes found cutting across the oldest layers.

[1] It is not to be denied that the later lavas breaking through earlier instrusives frequently show striking chemical relationships, and this is true of the province above referred to—but in general not such as could be explained by a remelting of the granitic magna a short distance below the surface. The chemical relationships may show consanguinity, but far from identity.

[2] These numbers are not sums of maxima—such would be much greater.

The zone of rock flowage, the characters of which have been so well set forth by Van Hise, is probably not completely established until we get considerably below the depths where Dutton would place lava reservoirs. One indication of this is that earthquakes have their foci at those and apparently often at considerably greater depths. Earthquake foci must be limited to the zone of fracture, for when with increasing "hydrostatic" rock pressure and temperature the strength of the harder rocks is well passed, we can hardly imagine a dislocation or other diastrophic movement that would be accompanied by seismic jars.

The depth to which certain sediments can be buried and then deformed without metamorphism—several miles, as shown by the thick Cretaceous formations of California and Oregon—indicates that the zone of chemical plasticity, as we may call it—the zone where readjustments take place by molecular (or atomic) interchange and recrystallization without rupture and yet without melting—is considerably below the limit set for volcanic reservoirs. But sediments and intercalated lavas have not uncommonly descended into this zone of chemical plasticity (as, for example, the Paleozoic-Mesozoic Bedrock complex of the Sierra Nevada, and other "regionally metamorphosed" formations), and indeed many thousands of feet below the upper limits of this zone, representing a burial beneath the surface of probably from 5 to 10, or possibly more, miles, and while there they are sometimes invaded by intrusive rocks from still farther down—rocks of a batholitic character, rising from a region wherein all of the necessary heat may easily be derived from the general interior supply. For, according to the curve presented by Strutt, 500° C. would be reached at about 8 miles, 600° at about 11 miles; and these temperatures are quite probably sufficient for granitic aqueo-igneous fusion. But, after these beds have been brought up again and exposed by deep erosion, we see no evidences of local reservoirs formed within them, though they may be cut through to their bases by various, often basic, dikes which may also cut down to an undeterminable depth through the granites.

Dutton suggests that, if an eruption occurred from a depth of 5 or 6 miles, "the temperature of the lava would be very high—probably a white heat—and the mass would be very great. Its conse-

quences might be disastrous beyond all precedent." He also doubts the possibility of a magma at 5 or 6 miles erupting at all. It seems, as stated above, that many Tertiary volcanoes received their material from beneath that depth of sediment. With present volcanoes it is impossible to say from what depth their magmas arise. One might be inclined to suspect, for example, that Mauna Loa and its companions, arising in a regular curve from the flat floor of the sea, received their molten rock from below the level of the ocean bottom, and, if so, as the mass rises 30,000 feet above this base, a lift of over 6 miles, followed by extrusion, would seem possible without any terrific outbreak. But Major Dutton explains this by considering that while the lavas were piling up the whole mass has been rising,[1] and the reservoir is in the protruded mass and considerably above the sea-floor.

The chief argument put forward for the shallowness of lava reservoirs is that volcanic earthquakes always have shallow foci. This is probably true. But whether they be due, as Dutton supposes, to the "fracturing or sudden yielding of the rock masses imediately above the lava reservoir," or whether they be due to gas or steam explosions, as commonly believed, we would expect them to be shallow. For the conditions which would make explosions possible (such as sudden relief of pressure by fracturing of solid obstructions and the consequent explosive expansion of water vapor, etc.) would probably only be found near the surface, however deep the magma originated, and fracturing could only take place in that superficial zone suggestively named the zone of fracture. The occurrence of such phenomena at slight depths seems therefore to have no bearing on the depth of the lava reservoir.

While the above considerations are believed to be incompatible with the particular form of volcanic theory under discussion, and with any theory postulating such shallow reservoirs, and while a pushing-down of the reservoirs toward the 15 or 20-mile limit makes less urgent and soon unnecessary the demand for a local special heat supply, the possibility of local radioactivity as an explanation still remains. But there are some considerations which appear to make improbable any theory of local strong radioactivity.

[1] See U. S. Geological Survey, *Fourth Annual Report*, p. 195 (1884).

The most striking phenomenon of recent vulcanism is the peculiar distribution of volcanoes. It is well known that the great majority of active volcanoes lie along two immense circles—the one encompassing the Pacific Ocean, and the other cutting this at an angle and passing through the Mediterranean region, the Himalayan region, and the West Indies. Many volcanoes occur outside of these two great belts, but in such cases are usually related to mountain chains either continental or submerged in a long line of islands, or to steep (generally rising) coast lines, or to long submarine plateaus or ridges. Without entering into any detailed discussion of these major volcanic lines, it may be asked: Why are there so many spots of local radioactivity —in other words, of peculiar chemical constitution—arranged at short intervals along these lines? A mere statement of the question shows that our theory demands too special and peculiar conditions. These same belts are well-known zones of seismic activity, but they are most fundamentally zones of diastrophic activity, and are closely related, commonly as bounding or separating tracts, to the earth's greater morphological units. Judged from the crustal evidences of earth movements and of the volcanic activities of the earlier periods, this relationship of volcanoes to critical morphological lines—belts of earth movement or diastrophic activity—has held throughout recorded geological time. If earthquakes, lines of upheaval, or other major movements and volcanoes are all dependent for their localization on the greater diastrophic activities, this striking association and alignment of them all would naturally be expected; but if the volcanoes depend for their origin on some irregular distribution of small patches of radioactive matter, this association and alignment are hard to understand.

Another characteristic of volcanoes which is considered a strong argument for a special theory of radioactivity is the repetitive nature of volcanic eruptions. The melting of rock by radioactive processes may easily be imagined to give rise to periodic outbursts of lava; but, even if the details of the process cannot be figured, would we not expect the same periodic character if volcanoes were an expression of diastrophic activity?

Earthquakes are commonly caused by movement along a "fault" plane; and this movement is apparently usually repetitive. The topo-

graphic peculiarities along the rift line of the recent great California earthquake indicate that faulting has taken place in recent time along the same line, and probably several times. In the great faults along the fronts of faulted ranges (the so-called Basin range type) the evidence is to the effect that the movements were repetitive and of moderate extent. Why should these phenomena take place in small spurts, with perhaps several years or even centuries of quiescence between? Why should not the mountain blocks rise, or the valley blocks fall at once with a great crash?

For a long period (post-Pliocene, however) a large part of the California coast (several hundred miles in extent) has been rising with respect to the sea. Its upward progress is marked by raised beaches and sharply incised terraces traceable to about 1,500 feet above the present sea-level. At San Pedro Hill Professor Lawson identified eleven terraces between sea-level and 1,240 feet. On San Clemente Island he determined eighteen between sea-level and 1,500 feet.[1] The upward movement has evidently not been uniform, but periodic, periods of activity being followed by periods of quiescence. And this is apparently true of all similar crustal disturbances.

Furthermore, the progress of older earth movements as preserved in the records of sedimentation, deformation of strata, and unconformities, shows that discontinuous movements and periodicity have characterized diastrophic history from the earliest geological times.

We should naturally expect, then, that vulcanism, if it is simply one phase or accompaniment or result of diastrophism, would partake of that universal and perhaps most striking characteristic of diastrophic processes, the alternation of periods of visible activity with periods of apparent rest, and the accomplishment of any general change by successive small increments, rather than by one great catastrophic effort.

What success shall we have if we try to get a concrete conception of a series of eruptions from a reservoir caused by locally concentrated radioactivity? A cubic mile of radium, or perhaps of pure pitchblende, if properly blanketed with rock, would probably in the course of time melt itself and its immediate surroundings, but we should have an eruption largely of radium or of pitchblende. How

[1] Lawson, "Post-Pliocene Diastrophism of the Coast of Southern California," *Bulletin of the Department of Geology*, University of California, Vol. I, pp. 115–60.

are successive eruptions to be brought about? We cannot reasonably imagine a solid mass of highly radioactive material melting a shell of rock about it and continually erupting that shell, the core remaining intact. We cannot reasonably imagine a great vessel with walls of a highly radioactive material melting its contents and erupting that, the walls remaining practically intact. The radioactive material must be largely scattered through the mass, and must therefore be in part erupted during the volcanic action. But is there enough radium or like material in lavas to melt them, if they were placed at a moderate distance beneath the surface, even taking the normal rise and surrounding active rocks into consideration? Apparently not. Have any large masses of pitchblende, or other possible especially radioactive material, ever been observed thrown out during volcanic eruptions? On the theory of local radioactivity they should be common.

It is well known that the basic lavas are highly heated when erupted. Granites are probably molten and active under hydrothermal conditions at a few hundred degrees Celsius; their structures and metamorphic effects demand but a moderately high temperature, possibly the least of any of the igneous rocks. Basalts flowing out on the surface require 1,000° or 1200° C., and are often at a higher temperature. But the remarkable fact is that basalts show the lowest radium content of any igneous rocks examined, while granites show the highest.

It is the writer's opinion that, while radioactivity may possibly explain a large part, perhaps all, of the present interior heat of the earth, it is incompetent to explain the special phenomena of volcanoes, although as an important general source of heat it may supply its share of the heat which figures in volcanic action.

It may some time be shown that certain peculiarities of some volcanoes as compared with others may be due to varying local radioactivity, but it would not seem that the characteristics of volcanic regions as compared with non-volcanic regions could be so explained. It appears that volcanoes must be looked upon as one type of results of the major normal diastrophic processes developed along the earth's critical mechanical lines, and that each volcano is not dependent for its general activity upon the special chemical composition of the crust immediately below its locus of eruption.